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Nano-scale multilayered composite coatings for cutting tools operating under heavy cutting conditions

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Abstract

The aim of this work was to create a methodology for the development of wear-resistant coatings. These coatings were deposited on the working surfaces of carbide inserts which were used for rough re-profile machining of railway wheels-sets. The coatings were formed using a filtered cathodic vacuum arc deposition (FCVAD). An investigation into the effect of the FCVAD process parameters on the composition and properties of the coatings was undertaken. The experimental work replicated industrial application conditions in terms of cutting speed (40–80 m/min), feed rates (0.8–1.2 mm/rev) and depth of cuts (4.0–8.0 mm). An increased tool life was achieved using carbide inserts with nanostructured multilayer composite coatings based on the Ti–TiN–TiAlCrN compound. The paper presents the results of carbide inserts with newly developed coatings for heavy duty machining of railway wheel-sets. The main coatings parameters i.e. microhardness, thickness, strength of adhesion of "coating-substrate" and surface morphology were studied. The nano-scale grain structure and thickness of sublayers for each coating component allowed achieving a balanced wear of rake and flank surfaces without micro/macro chipping of contact areas and cutting edge of the inserts. The results presented here show that the cutting tool life of the inserts with the new wear-resistance coatings exceeded commercial coated tools by a factor of more than two.

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1. Introduction

One of the most difficult and heavy-duty cutting operations is the re-profiling reductive machining of rolling surface of rail wheel-sets. This is because the wheel sets are exposed to "shock peening", during their operation when the surface layer of wheel-sets acquires an increased fragility with low fatigue strength leading to an increased probability of sudden failure [1, 2, 4, 7]. The defective surface layer of wheel-sets has a hardness over 55–60 HRC which is removed with cutting depths exceeding 5–6 mm. This creates extremely heavy loading conditions on the tool because of the occurrence of high thermal-mechanical stresses, the sign of which alternates. The practice of forming and re-profiling of rolling surfaces of railway wheel-sets widely uses processes such as turning, milling and abrasive machining. However, turning is mainly used to profile the rolling

surfaces of rail wheel buggies [1, 2, 4, 7].

Several types of carbide inserts are used for turning of the rolling surfaces of wheel-sets. Carbide inserts are made of various types of carbide in mass production, thus the manufacturing quality and the performance characteristics of the carbide inserts greatly vary [7]. This variation has a negative effect on the efficiency and the quality in re-profile machining of railway wheel-sets. This increases the cost of cutting tools and the manufacturing process as whole [1, 2, 4, 7].

A brief analysis of the requirement of carbide inserts used in this production showed that, the annual average cost of cutting inserts reaches tens of millions of US dollars [7]. Consequently there is a need in improving the efficiency of the carbide inserts used in re-profile machining of hardened surfaces of railway wheel-sets [3, 4, 7]. A successful improvement in tool life of carbide insert would bring a large cost saving in the process of retro-fitting railway wheel-sets

and in the purchase of cutting tools.

With this purpose, this paper investigates ways of increasing the wear resistance of the P20-P30 carbide inserts. This was achieved by applying wear-resistant coatings to the inserts used in this type high-performance re-profiling heavy machining.

A concept of multilayered coatings with nano-scaled grains allows obtaining coating with several sublayers at nano-scale thickness, [6, 8, 11]. In functional coating, there exist several ways of improving coating performance, however, the multilayered approach is the most promising method in functional coatings for heavy cutting conditions [6, 8, 9, 11, 13, 14]. This new method of coating increases the surface hardness, heat and wear resistance of the tools. These coatings are characterized by a high interlayer adhesive strength, a low level of internal stresses, and a balance of hardness and toughness. Coatings developed using this method have an increased crack resistance and they retain their cutting efficiency without damage or flaking from substrate for a longer period of operation. The performance stays stable even under thermoplastic deformations of the cutting edge and under cyclic thermo-mechanical stresses [1-5].

It is known that the fracture of materials with standard grain structure (i.e. grain diameter greater than 1 μm) is primary caused by the formation of cracks arising from the concentration of dislocations of various defects [8]. The grains in nano-scale materials have a diameter, which is less than 80...100 nm, therefore, the fracture mechanism here is different in nature [4-7, 8]. In such materials, the inter-granular boundaries processes are the predominant causes of fracture. This is because there is a relatively smaller number of atoms in the grains themselves compared to the number of atoms in the boundaries. This particular property largely transforms the inter-granular interaction and leads to the inhibition of movement and the generation of dislocations. This effect, in its turn prevents the nucleation of cracks, their branching and propagation, because of the hardening process at grain boundaries.

Dislocations in nano-grains hardly occur because of a complete inhibition at their boundaries, thus the boundaries begin to have a crucial role in the deformation and fracture of nano-material. This characteristic allows creating unique properties in nano-crystalline materials especially with grain size below 5~10 nm. This gives an advantage in predicting the formation of subatomic nano-crystalline structures and the corresponding directional change in the properties of materials.

Given the high adhesive strength between the coating and the substrate, along with the chemical passivity of the coating material relative to the processing material, it is possible to predict with confidence the increase in endurance and wear resistance of cutting tool with multilayered composite nano coatings. This prediction is effective for any mechanisms of tool wear and fracture under the following modes: ductile, brittle, abrasive, adhesive-fatigue, chemical-oxidation, diffusion, [6, 8, 11, 12].

Thus, the main of this study was to increase wear resistance of carbide inserts under heavy conditions of re-profiling

machining of railway wheel-buggies by applying multilayered nano composite coating to the cutting tools.

2. Experimental

2.1. Nano- coating Process

A new process called Filtered Cathodic Vacuum Arc Deposition (FCVAD) was used to deposit coating on a set of carbide inserts. Here the VIT-2 rig was used along with the FCVAD to control the structure of coatings creating sublayers at nano-scale. To achieve nano-grain and nano sublayers the following techniques were used:

- (a) An additional energy was supplied to the deposited coating to convert the kinetic energy of bombarding ions into thermal energy in local volumes of substrate material. This was followed by a cooling stage at extremely high speed of about 10^{14} K/s;
- (b) Increase the density of islands (centers) of the coating nucleation;
- (c) Stimulate plasma-chemical reactions of compounds synthesis while introducing thermal energy directly into surface to promote the mobility of atoms;
- (d) Stimulate the diffusion processes at the boundary interface between coating and substrate to increase the strength of the adhesive bonds.

To control the grains size and the crystal-chemical structure, the energy and the flux density of bombarded ions was varied using FCVAD processes. The FCVAD process allowed developing a new technology to apply coatings to carbide inserts which were used for heavy machining in re-profiling work-hardened surface of railway wheel-sets. In this process, a methodological approach was used to ensure that the composition, the structure and the properties of each layer of the coating met the requirements of external thermo-mechanical loads on the tool. Additionally, the coatings should play the role of an intermediate technological environment between tool and machined materials to maximize the efficiency of the machining operations [10, 11].

A three-component coating structure was developed to operate successfully in heavy machining conditions. Each layer of the coating architecture has a nano-scaled multilayer composite structure, which has a high resistance to failure/fracture with hindrance to the formation and propagation of micro-cracks. This is because the formation of crack leads to micro/macro chipping of coatings which increases the tool wear. In addition, the engineered architecture of the coatings effectively increases the resistance to adhesive-fatigue wear of the tool in heavy cutting conditions [7, 8, 10].

The above mentioned three-component coating architecture consists of: an outer layer, an intermediate layer and an adhesive underlayer. The outer layer is wear resistant and is in direct contact with the material to be machined. Thus it has the key function of reduce the physical and chemical activity of the cutting tool material and to weaken the adhesion with the workpiece material. The intermediate layer has the primary function of supporting the working capacity of the wear resistance outer layer and implementing a strong adhesion with the outer layer and the adhesive sub-layer. Additionally, the intermediate layer reduces the intensity of

heat flow from frictional heat sources and it obstructs the diffusion processes between the work and tool materials. The intermediate layer has a tribo-passive property and can be employer as sensor for monitoring the fluctuation in the cutting temperature and the level of thermo-mechanical stresses arising at tool–chip and tool–work interfaces. The adhesive under-layer has a direct contact with the tool material, thus it has the primary function of providing strong adhesion between tool material and the coating.

The selection of the composition and properties of upper layer of coating was based on the universal mechanism of adhesive-fatigue wear of cutting tool as this wear model is well reported. Using this model, the lost of the tool weight M_ϕ due to wear was calculated based on the method described in [8, 10]:

$$M_\phi = K_a \cdot \rho \cdot F_a \cdot (J \cdot \sigma_a / \sigma_p),$$

where K_a is the adhesion coefficient (volume); ρ is the density of tool material; J is the adhesion intensity; σ_a is the bond strength in adhesion centers; σ_p is the tool material resistance to fracture; F_a is the nominal contact area. The key in this study is to ensure the weight loss of the tool is minimum i.e. $M_\phi \rightarrow \min$

While using the adopted methods, a quality evaluation was undertaken to identify the conditions when intensive adhesion starts and the tendency to adhesive interaction of the tool with the machined materials. Such tendency increases under the following conditions:

- (a) with the increase in temperatures (up to the beginning of intensive oxidation and softening of adhesion bridges);
 - (b) with the increase in the frequency of natural oscillations of valence atoms that correlates with the statistical weight of atoms of the most stable electron configurations (SWASC);
 - (c) with the increase in rate of dislocation mobility, which is inversely proportional to hardness of tool material (coating).
- To improve the adhesion between the coating and the tool material (substrate) when forming the functional coatings, metal adhesive underlayers such as Ti, Zr or nitrides of transition metals (TiN, ZrN) or sublayers of metal nitrides (TiN, CrN, ZrN), were introduced between the material of coatings and substrate. The intermediate layer was designed based on Ti-N, Cr-N, Ti-Al-N, Ti-Cr-N, Ti-Cr-Al-N to produce composite coatings with total thickness acceptable for general purposes.

The procedure for the preparation of tool samples in this study included a preliminary chemically activation cleaning using ultrasound with subsequent fine cleaning with spirit and rubbing with flannel. The samples were mounted in special devices and placed in the vacuum chamber of the VIT-2 rig, which incorporates the FCVAD process technology. The rig was equipped with a planetary mechanism to rotate the samples in the vacuum chamber at different speeds in the range of 1-5 rpm. After creating vacuum at a pressure of 0.01 Pa, the samples were subjected to fine cleaning by bombarding sample surfaces with argon gas ions or metal ions (Ti, Zr, Cr). This was followed by a thermal activation of the samples with electrons generated by glow discharge, with subsequent coating process. The outer layer of the three-component coating (i.e. Ti-TiN-TiCrAlN) was deposited using the following FCVAD process parameters: bias voltage on substrate was up to 205-210 V; nitrogen

pressure was $2.6 \cdot 10^{-10}$ Pa; ion current density was 0.5 A/mm². The arc current was set for: $I_{Ti}=75-90$ A; $I_{Al}=100-120$ A; $I_{Cr}=65-80$ A. The deposition time τ was between 60-70 min.

2.2. Study of coating properties

Microstructural studies of wear-resistant coatings were performed using electron scanning microscope Jeol- LSM-6480LV with an add-on device for energy-dispersive spectrometry Inca Entergy Dry Cool (Oxford Instruments). An add-on device for energy-dispersive spectrometry was used to measure element composition of coating layers. It allowed obtaining the distribution of elements along a line within a given area. In addition it allowed evaluating the composition of epitaxial layers and their thickness. To obtain more details into the microstructure of coating surface relief, a field emission electron scanning microscope JSM-6700F with the JEOL-JTD-2300F energy-dispersive spectroscopy were used. The macroscopic properties of the multilayered composite coatings, such as thickness, hardness, friction coefficient and strength of adhesion of the coating to the substrate were also determined. In particular, thickness of coatings was measured using Calotest and reverse β -radiation with a Fisherscope-MMS. To assess the microhardness of the coatings, including the thickness a nanotester A-600 (Micro Materials Ltd UK) was used. This allowed to measure the microhardness at an "oblique thin section" or at the end of the reference sample with locality of 100 nm.

2.3. Tools performance with nano-composite coatings

This study focused on the cutting properties of carbide inserts type P30 coated with the newly developed nano-scale multilayered composite. This investigation was conducted in dry turning of work-hardened surface of railway wheel-sets on a heavy turning lathe type Rafamet UCB-125 and UBB-112. The following machining parameters were used: cutting speed, $v = 40-80$ m/min; feed rate, $f = 0.8-1.2$ mm/rev; and depth of cuts, $a_p = 4-8$ mm.

The working efficiency of the coated inserts was evaluated by wear resistance coefficient with to an uncoated insert P30 taken as baseline. During the tests, a limiting flank wear $VB_{max} = 0.5$ mm and a coefficient of tool life variation (v) was considered. In this particular test, 60 min were needed to deposit the multilayered composite coating on the inserts.

The main coatings parameters i.e. microhardness, thickness, strength of adhesion of "coating-substrate" and surface morphology were studied. The composition of the layered structure of Ti, Cr, Al composite was investigated and controlled. The results of the main parameters, surface, structure and morphology of developed functional coatings Ti-TiN-TiCrAlN are presented in Table 1.

The analysis of the data in Table 1 showed that the wear-resistant layer (Ti,Cr,Al)N has a multilayered structure with the thickness of sublayers down to 15-25 nm. The mean ratio of Ti, Cr and Al in the wear-resistant layer of TiCrAlN was 0.2, 0.2, 0.2 respectively. $Ti_{0.2}Cr_{0.2}Al_{0.2}N_{0.4}$ -layer had a columnar structure oriented perpendicularly to the plane of TiN-underlayer. The thickness of the sublayers in the intermediate TiN-layer was in the range of 25 nm as illustrated in Fig. 1, and for this reason, the multilayered composite coating are considered as nano-coating [6,

8,16,17].

Table 1. Architecture and parameters of layered functional coatings based on the composition Ti-TiN-TiCrAIN obtained using FCVAD

Architecture of coating elements	Composition, %, thickness	Microhardness, GPa*	Strength of coating adhesion**, P_{cr} , N
Adhesion underlayer Ti (monolayer)	$h_a=0.2-0.3 \mu\text{m}$	-	
Intermediate layer TiN (multilayered)	$h_n=1.8 \mu\text{m}$ $h_c=15 \text{ nm}$	-	120
Wear-resistant layer $\text{Ti}_{0.2}\text{Cr}_{0.18}\text{Al}_{0.11}\text{N}_{0.5}$ (multilayered)	$\text{Ti}_{0.2}\text{Cr}_{0.18}\text{Al}_{0.11}\text{N}_{0.5}$ $h_n=2.0 \mu\text{m}$ $h_c=25 \text{ nm}$	32.0	

h_a is the thickness of the adhesion underlayer; h_n , h_n is the thickness of the wear-resistant and the intermediate layers; h_c is the thickness of the sublayers of wear-resistant and the intermediate layers; * is the surface microhardness obtained with a nano-indenter;

** P_{cr} is the critical value of the force applied to the indenter scribing (scratching) the coating until deterioration occurred along the scratch.

Microdroplets formation is inherent to the vapor deposition technologies. These droplets can be formed at the surface of TiCrAIN-layer, in the outer layers of the coating and at the boundaries of "coating- substrate" section. However, with FCVAD the formation of microdroplets is minimized (less than 10 percent), and this drastically increases the quality and reliability of the coatings. Fig. 2 illustrates the microdroplets formed in a standard arc PVD (Fig. 2a) and the new FCVAD in Fig. 2b.

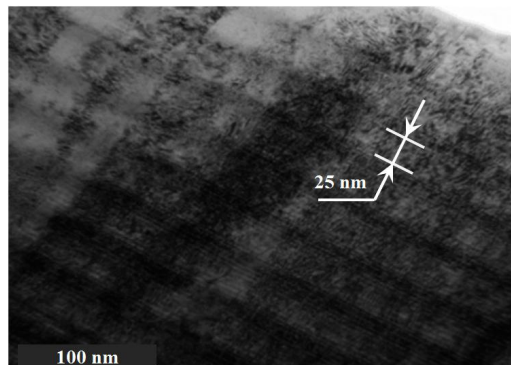


Fig.1. SEM micrograph of a cross section of carbide insert coated with Ti-TiN-Ti_{0.2}Cr_{0.2}Al_{0.2}N_{0.4} (FCVAD technology).

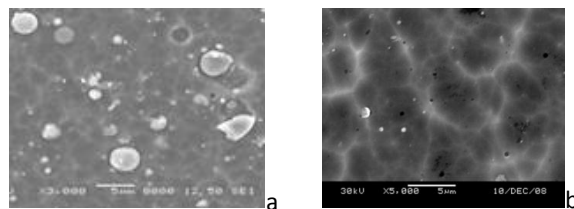


Fig. 2. SEM micrographs of coated surfaces: (a) standard arc-PVD; (b) FCVAD technology.

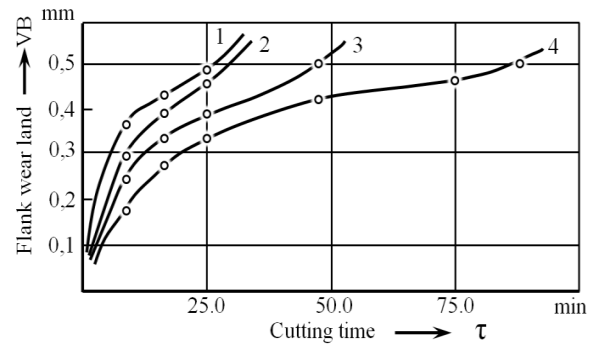


Fig 3. Dependence of flank wear VB_{max} on cutting time τ in rough re-profile machining of railway wheel-sets

Machining parameters:

$v = 60 \text{ m/min}$; $f = 1.0 \text{ mm/rev}$; $a_p = 6.0 \text{ mm}$;

Coating structure:

1- TiN-TiCN-TiN (CVD);

2 -TiCN-Al₂O₃-TiN (CVD);

3 -TiC-TiCN-TiN (CVD);

4- nano-structured coating Ti-TiN-TiCrAIN (FCVAD).

Fig. 3 depicts the performance of coated carbide inserts using different composition of coating materials. Sample 1, 2 and 3 are coated using commercial CVD technology whereas sample 4 was coated using the new FCVAD technology. It is observed here that sample 4 with the new nano-coating outperformed commercially available products. Within the wear limit of 0.5 mm, it is seen that the new nano-composite coating allowed sample 4 to have a stable performance up to 88 min after a conditioning period of 25 min, whereas the other sample i.e. 1, 2 and 3 did not show any stabilized operational period.

During heavy re-profiling machining of railway buggies it was found that the most intensive wear of the tools under investigation was in the inserts coated using CVD technology. Commercial CVD technology employs higher temperatures in the process and the time of deposition of the coatings is longer than the time required to deposit similar coatings using arc-PVD. Several researchers [8, 12, 14] pointed out the CVD process is characterized by the formation of cobalt fragile η -phase (like $\text{W}_3\text{Co}_3\text{C}$) at the interface between the tungsten carbide and the coating (WC, TiC). This reduces the strength of tungsten carbide by 15-20%. Consequently, this increases the probability of brittle microfracture at the contact areas of carbide tools. In the filtered cathodic vacuum arc deposition (FCVAD), use for the innovative deposition of nanoscale multilayer composite coating Ti-TiN-TiCrAIN, the time and temperature of the deposition is significantly short and this prevents the formation of η -phase that leads to an embrittlement of the carbide substrate.

In addition, the nanoscale multi-layered coating with sublayers at nano- thickness developed in this study allowed the system (tool-coating) to have a rather high resistance to the formation, growth and branching of cracks. This key property prevents brittle macro/micro fracture of contact areas and tool cutting edge. The aforementioned is demonstrated Figure 4, where the micrographs put side by side the wear of cutting inserts with commercial coatings and the newly developed coating in heavy re-profile machining of wheel-sets

after 25 minutes cutting process.

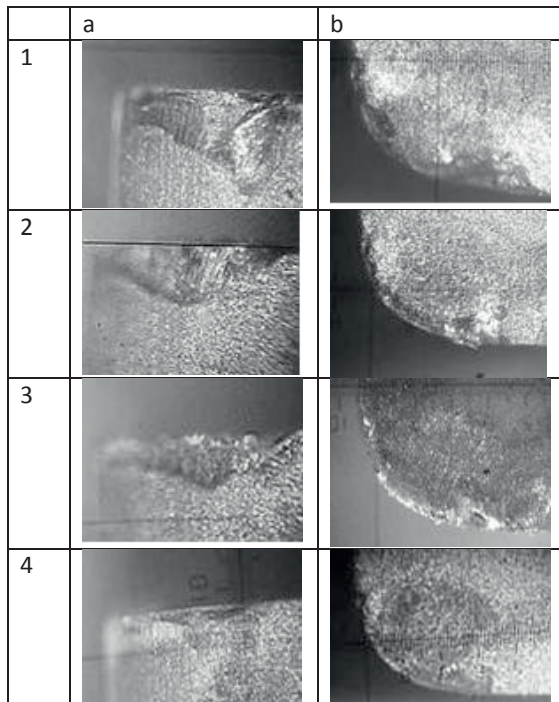


Figure 4. Wear characteristics after 25 min turning at $v = 60$ m/min; $f = 1.0$ mm/rev and $a_p = 6.0$ mm: (a) flank face; (b) rake face; 1 – TiN-TiCN-TiN (CVD); 2 – TiCN-Al₂O₃-TiN (CVD); 3 – TiC-TiCN-TiN (CVD); 4 – Ti-TiN-TiCrAlN (FCVAD).

It is observed in Figure 4 (column 4) that inserts with the new coating Ti-TiN-TiCrAlN after 25 minutes heavy turning of work-hardened railway wheel-sets have a minimum and balanced wearing of the rake and flank surfaces without chipping and spalling. However in column (1-3) illustrating inserts with commercial coating the typical macro and micro chipping of contact areas and tool cutting edge is observed. This leads to an increased tool wear.

The results of comparative tests of wear resistance of inserts with Ti-TiN-TiCrAlN coating (thickness $h_n = 3.5 \dots 4.0$ μm) relative to the wear resistance of similar inserts with the latest generation of commercial coatings are presented in Table 2. This study revealed a high efficiency of inserts coated with the developed nano-scale multilayered composite coatings in comparison with commercial countertypes under heavy duty re-profiling turning of rolling surface of wheel-sets. In particular, this study showed that the average tool life was high (88.1 min) and the coefficient of wear resistance K_{CT} was high (2.19). In addition, a reduction in coefficient of tool life variation ($v = 0.355$) was observed. The latter indicates significant increase in the reliability of the inserts in high-performance re-profile turning of defective surface of wheel-sets under heavy loads conditions.

Table 2. Results of comparative tests of wear resistance of various inserts - LNM shape

Sample	Coating Composition & architecture	Coating thickness, μm	Tool life, min	Coefficient of variation, v	Wear resistance Coefficient $K_{CT} = T_C/T^*$
1	TiN-TiCN-TiN	9.0	45.6	0.448	1.18
2	TiCN-Al ₂ O ₃ -TiN	10.0	26.4	0.452	1.05
3	TiC-TiCN-TiN	10.0	25.0	0.46	0.64
New coating	Ti-TiN-TiCrAlN	4.0	88.1	0.355	2.19

* T_C is the average tool life with coating; T is the average value of wear resistance of the tool without coating.

Conclusion

Re-profile machining of railway wheel-buggies widely uses high-performance cutting operations and requires a large consumption of expensive carbide tooling which lead to high costs of machining. Currently, re-profile machining of wheel-set are increasingly using coated carbide tools. However, the durability of coatings at the contact areas of the tool is extremely poor, due to non-stationary cutting conditions associated with high contact stresses and their variability that lead to macro/micro-spalling, plastic deformation of cutting tool edges. This inevitably leads to failure of the coatings applied to the working surface of carbide inserts using chemical deposition (CVD), which in fact drastically reduces the plastic strength of carbide. Despite a continuous improvement of carbide substrate and coating methods the efficiency in re-profiling machining operations is still low.

Consequently, this paper considered a methodology of forming wear-resistant coatings which were successfully deposited on the working surfaces carbide inserts designed for rough re-profile machining of railway wheels. The proposed nanostructured multilayer composite coatings were produced using a new process of filtered cathodic vacuum arc deposition (FCVAD). This approach allowed implementing the concept of a three-component coating systems and nanostructured multilayer composite architecture. An important feature of this process is that, FCVAD has low impact on the surface structure of the cemented carbide; therefore, it does not lead to a reduction of the plasticity and strength of the substrate.

The research findings presented in this paper show a dependence of the deposition conditions on the basic parameters (composition, properties, thickness, adhesion to the tungsten carbide substrate). These findings were applied to solve successfully an industrial problem where the developed coating composition based on Ti-TiN-TiAlCrN was deposited on a set of inserts which outperformed commercial counterparts in rough re-profile machining of railway wheel-buggies.

The features and wear profile of carbide inserts with the coatings elaborated were studied in replicating actual industrial in rough re-profile machining of railway wheel-sets.

The results of this comparative study showed that the developed coatings drastically improved the performance of the inserts. This extended the operational tool life of these inserts over the commercial counterparts. Inserts with new coatings had a low wear rate which implies a different wear mechanism where there is no chipping or flaking as observed in samples 1-3 where commercial CVD process was applied.

The FCVAD process allowed creating nanometric grain structure and thickness of sublayers for each component of the coatings. This allowed increasing the hardness and heat resistance of cemented carbide with a good balance between plasticity and strength.

It was also shown that the manufacturing processes of the coating radically differ one from another. On the one hand, the CVD is characterized by high temperatures which induce brittleness of substrates. On the other hand the conventional arc-PVD engenders large droplets, which damage the coatings in terms of hardness and adhesive strength. However the new FCVAD eradicate all these problems securing minimum droplets, high adhesive strength, no embrittlement and better micro hardness with subsequent improved tool performance.

The comparative experimental study in roughing re-profile machining in heavy duty conditions with depth of cut of 4-8 mm showed that the inserts with the new coatings had substantially higher wear-resistance than commercial ones. There was no chipping, no micro/macro spalling of contact areas and tool cutting edge. The experimental result showed that the operational life of the inserts with the elaborated coating exceeded by a factor of more than two the lifetime of commercially coated inserts.

References

- [1] Bu, J.-L., Li, F., Fu, M.-H., Huang, Y.-H. Research on wheel/rail action of heavy haul train. Zhongguo Tiedao Kexue/China Railway Science Volume 26, Issue 5, p. 52-56.
- [2] Chia-Han Lai, Keng-Hao Cheng, Su-Jien Lin, Jien-Wei Yeh Lierat Mechanical and tribological properties of multi-element (AlCrTaTiZr)N coatings. Surface & Coatings Technology 202 (2008) P. 3732–3738
- [3] S. PalDey, S.C. Deevi. Single layer and multilayer wear resistant coatings of (Ti,Al)N:a review. Materials Science and Engineering A342 (2003) p.58-79
- [4] Shevtsov, I.Y., Markine, V.L., Esveld, C. Optimal design of wheel profile for railway vehicles. Wear, Volume 258, Issue 7-8, p. 1022-1030
- [5] Cheng, Y. , Liu, X. , Li, Z., Liu, L., Wang, H. Jixie Gongcheng Xuebao. Adhering failure of the tool-chip in the process of extremely heavy cutting. Journal of Mechanical Engineering Volume 48, Issue 19, 5, p. 169-176.
- [6] Fox-Rabinovich, G.S., Endrino, J.L., Agguire, M.H., Beake, B.D., Veldhuis, S.C., Kovalev, A.I., Gershman, I.S., Yamamoto, K., Losset, Y., Wainstein, D.L., Rashkovskiy, A. Mechanism of adaptability for the nano-structured TiAlCrSiYN-based hard physical vapor deposition coatings under extreme frictional conditions. Journal of Applied Physics Volume 111, Issue 6, 15 March 2012, Article number 064306.
- [7] Vereschaka A.S., Kulikov M.Yu., Vereschaka A.A., Florov A.V., Popov A.Yu., San Maung. Improvement of working capacity of carbide tools for machining rail wheel pairs. Key Engineering Materials Vol. 581 (2014) Trans Tech Publications, Switzerland. p. 9-13
- [8] Vereshchaka, A.A., Vereshchaka, A.S. , Mgaloblishvili, O., Morgan, M.N., Batako, A.D. Nano-scale multilayered-composite coatings for the cutting tools. International Journal of Advanced Manufacturing Technology, Springer-Verlag, 2014, p. 1-15.
- [9] Vereschaka, A.A., Volosova, M.A., Grigoriev, S.N., Vereschaka, A.S. Development of wear-resistant complex for high-speed steel tool when using process of combined cathodic vacuum arc deposition (2013) Procedia CIRP 9 PP. 8 - 12
- [10] Vereschaka A.S.. Working capacity of the cutting tool with wear resistant coatings, Moscow, Mashinostroenie (1993), p.336
- [11] Vereschaka Alexey. Improvement of working efficiency of cutting tools by modifying its surface properties by application of wear-resistant complexes. Advanced Materials Research, Vols.712-715 (2013) Trans Tech Publications, p.347-351.
- [12]. Panckow A.N, Steffenhagen J., Wegener D., Dubner L., Lierath F. Application of novel vacuum-arc ion-plating technologies for the design of advanced wear resistant coatings. Surface and Coating Technologies 138 (2001). p. 71-76.
- [13] Grigoriev S.N., Vereschaka A.A., Vereschaka, A.S., Kutin A.A. Cutting tools made of layered composite ceramics with nano-scale multilayered coatings. Procedia CIRP 1 (2012), p.318–323.
- [14] Konstantinos-Dionysios Bouzakis, Nikolaos Michailidis, Georgios Skordaris and others. Cutting with coated tools: Coating technologies, characterization methods and performance optimization. CIRP Annals [10] Manufacturing Technology 61 (2012) p.703–723.
- [15] Tonshoff, H.K., Arendt, C., Ben Amor, R. Cutting of hardened steel. CIRP Annals - Manufacturing Technology Volume 49, Issue 2, 2000, p. 547-566
- [16] Vereschaka, A.A., Vereschaka, A.S., Grigoriev, S.N., Sladkov, D.V. Nano-scale multi-layered coatings for cutting tools generated using assisted filtered cathodic-vacuum-arc deposition (AFCVAD) (2013) Applied Mechanics and Materials 327 PP. 1454 – 1459
- [17] Vereschaka, A.A., Vereschaka, A.S., Grigoriev, S.N., Kirillov, A.K., Khaustova, O.U. Development and research of environmentally friendly dry technological machining system with compensation of physical function of cutting fluids. (2013) Procedia CIRP 7 PP. 311 - 316